nature sustainability

ARTICLES

https://doi.org/10.1038/s41893-020-0537-2

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Impacts of a large-scale titling initiative on deforestation in the Brazilian Amazon

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Across carbon- and biodiversity-rich tropical forests, titling initiatives are implemented with the goal of regularizing land tenure and decreasing deforestation. However, the effect of tenure security on deforestation is theoretically ambiguous, and credible empirical evidence is lacking. We analyse the responses of 10,647 landholders between 2011 and 2016 to a large-scale land-titling programme called Terra Legal in the Brazilian Amazon, set to regulate an area as big as Germany and France combined. Using a fixed-effects regression modelling strategy and property-level data, we managed to explore the causal chain between land titling and deforestation. Contrary to expectations, we find evidence that small and medium landholders increased deforestation in response to the programme, whereas large landholders remained largely unaffected. Landholders with property titles deforest more as crop and cattle prices increase, indicating greater market integration at the expense of conservation. Our results suggest that titling alone without greater coordination with other policies will not yield the expected environmental benefits.

Slowing deforestation in the Amazon rainforest has been a central environmental issue for decades, driven by concerns about declining ecosystem services, biodiversity loss and growing carbon emissions[1]. With increasing worries over catastrophic climate change, scientists and policymakers have intensified their attention on forest conservation as a means to advance climate goals. Several studies suggest that forest conservation could contribute up to 40% of the needed greenhouse gas emissions reduction to mitigate climate change, with particular importance attributed to Brazil, which has 13% of global remaining forests[2–4].

To address these concerns, several policies have been implemented in Brazil to curb deforestation on private and public properties, including enhanced satellite monitoring[5], zero-deforestation supply chain agreements by the private sector[6], credit restrictions for municipalities with high deforestation[7] and more stringent enforcement of Brazil's Forest Code[8,9]. These efforts have focused primarily on reducing deforestation on large properties and have played an important role in lowering deforestation rates since their peak in 2004. Nonetheless, deforestation has recently been increasing again at a worrying pace, reaching a ten-year high in 2018 (ref. [10]). One important reason for this renewed negative trend is that deforestation on small holdings (relative to larger properties) has gone up substantially over time[11,12]. Overlapping or non-existent tenure rights in the Brazilian Amazon, particularly on smaller properties, are seen as a central catalyser for high deforestation rates, yet this empirical hypothesis remains largely underinvestigated.

Addressing this research gap is crucial (as discussed in detail in the Supplementary Information), as many tenure-right programmes are partly justified on the grounds of yielding beneficial environmental outcomes. Yet, there are compelling theoretical reasons whereby under different institutional and market settings, altering tenure arrangements may lead to countervailing impacts with respect to deforestation rates[13]. Also, the mediating role of other plot-specific characteristics, most notably the sizes of land holdings in the affected area, can sway the impact of changing tenure arrangements on deforestation in ambiguous directions[2]. Such countervailing effects are poorly understood, and hence the often-held default conservation presupposition that promoting individual private tenure arrangements will lead to greater ecological benefits must be taken with caution.

We analyse the causal links connecting forest land tenure, property size and observed deforestation rates in the Brazilian Amazon. In particular, we examine the impacts on deforestation associated with the Brazilian Terra Legal Programme (TLP), one of the largest land-titling programmes in the world, which since 2009 has been assigning property rights to undesignated public lands in the Legal Amazon (comprising all nine Brazilian states in the Amazon basin) corresponding to an area the size of France and Germany combined[14]. The programme focuses on so-called 'undesignated public areas', which are de jure public plots of land but on which private landholders have lived and farmed. Under the TLP, landholders receive a conditional title if they can prove effective cultivation of the land before July 2008 (the latter condition was set to avoid incentives for land-grabbing and legalization through the programme). In addition, the title remains conditional for ten years, while landholders need to show that they follow the requirements of the Forest Code, which prescribes that 80% of the forest in the Amazon is set aside for nature protection. If landholders comply with these stipulations for the provisional period, then they receive the final title, which grants full property rights over the land in question. Importantly, farmers are not allowed to sell the land during the provisional period, but can use it as collateral for loans.

To assess the impact of this programme on deforestation rates, we use a unique dataset that covers 10,647 landholders over a period of six years (63,882 observations). We use these detailed panel data to investigate whether such improved tenure rights actually lead to greater conservation of forest or to increased investment and deforestation. Our data complement previous studies in several important ways. First, prior studies have primarily focused on the land rights of indigenous communities[15,16]. However, these communities

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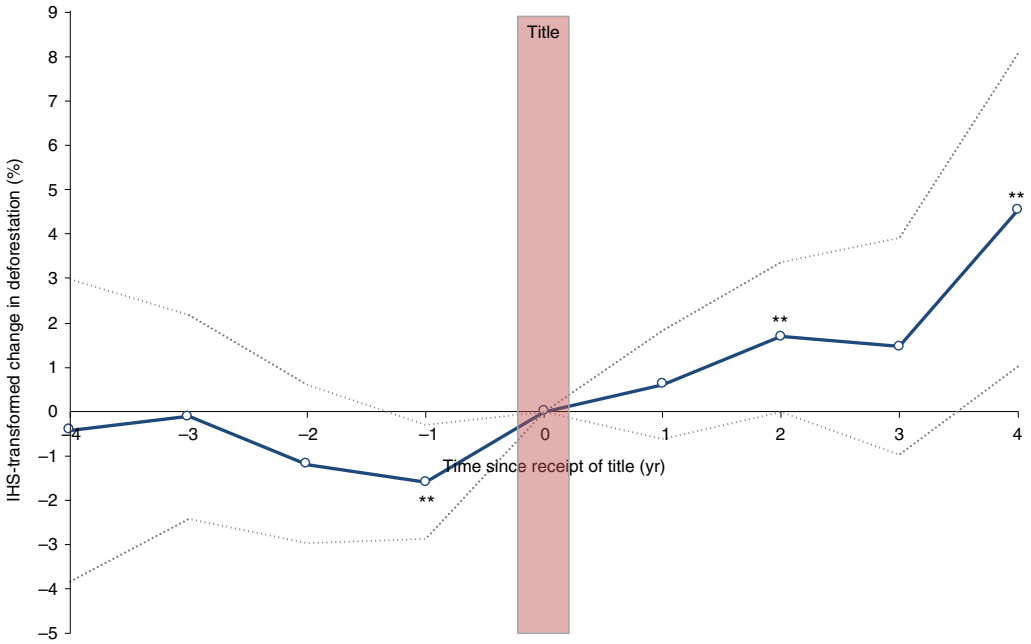

Fig. 1 | Event study on the effect of receiving a title on deforestation. The full table is in the Supplementary Information. The following are included as control variables: year, beef prices, crop prices, agricultural suitability and distance to roads (the latter two interacted with the year variable). IHS refers to the inverse hyperbolic sine transformation, commonly used when a log transformation is not possible due to zeroes in the data. The dotted lines indicate the 95% confidence interval. $^{**}P < 0.05$.

differ markedly from small farmers in a variety of ways, as do the property rights conferred on them. For example, indigenous community lands in the Brazilian Amazon are held in common ownership and may not be transferred or used as collateral. In addition, the territory covered by indigenous community lands tends to be more remote, and therefore less subject to deforestation pressure. Furthermore, previous analyses (focusing mostly on indigenous communities) have used mostly small sample sizes covering limited time periods.

By focusing on a specific timescale, geographical region and population, our analysis is a highly policy-relevant and informative complement to prior studies for exploring the impact of property right reforms on deforestation in the Amazon. Furthermore, our main question is of great interest to other developing and emerging countries with high levels of tropical forest and deforestation pressures, such as Indonesia. Property right reforms come with financial, social and political costs, while they have ambiguous consequences on deforestation[13]. It is therefore imperative to augment our understanding of the impacts of introducing such reforms through robust empirical analyses. In addition to contributing to the literature on the environmental consequences of tenure regularization, our paper speaks to a broader strand of literature on whether secure tenure can act as a catalyst for economic development and social reforms[17]. For example, previous studies show that regularizing land tenure supports the rule of (forest) law, enabling the development of land, labour and commodity markets as well increases in taxation revenues[18]. Emerging evidence also suggests that it could lead to positive social impacts, such as improved gender equality and conflict resolution[17,19].

The central empirical challenge in studying the effect of land rights on deforestation is finding a credible counterfactual. It is common in titling studies to use untreated land as a counterfactual (that is, land not subjected to land-right changes). However, such land is commonly untreated for non-random reasons, and it might differ from treated land in ways that are not readily measurable. The data used in this paper allow us to address these challenges. Our sample includes 10,647 properties whose land tenure was regularized under the TLP between 2011 and 2016. By exploiting plausibly exogenous variations in the timing of tenure formalization, we use a panel approach that controls for landholder-specific fixed effects and time-varying covariates. In addition, our study offers quasi-experimental evidence on the effect of private land rights on deforestation outcomes in Brazil and complements studies on the effect of environmental registries such as the Cadastro Ambiental Rural (CAR)[2,8,20,21].

Results

Our empirical analysis suggests that landholders that received the land title increased deforestation rates as a response to the programme. First, as our event study in Fig. 1 shows (the full table is in the Supplementary Information), the effect of the title only fully materialized two to four years after the title was received. A significant 1.7% increase in deforestation after two years and a 4.6% increase after four years can be observed. Second, it is important to underline that anticipatory behaviour (farmers who might deforest less in the year before receiving the title so as not to jeopardize receiving the title) is also influencing our estimates, as farmers reduce deforestation by 1.6% on average the year before receiving the title. Hence, we probably slightly overestimate the impact of receiving a title on deforestation if this anticipatory behaviour is considered. We further decompose this effect for different sizes of plots in Table 1 and Fig. 2 to show that this overestimation holds true only for small properties.

To explore the mechanism behind the uptick in deforestation on registered plots, we compose detailed price indices for crops and beef to study whether formalizing land tenure also leads to greater access and integration into agricultural markets. Our results from Tables 2 and 3 indicate that farmers with regularized land titles respond more strongly to market signals once their land becomes regularized. These results show that the effect of titling on deforestation is mediated strongly—and very significantly—by cattle price. As Table 3 indicates, a 10% increase in the cattle price index leads

Table 1 | Effect of titling on annual deforestation

Heterogeneous effect of titling on annual deforestation by property size

	Overall	Small	Medium	Large	Weighted
Probability of clearing	0.008** (0.004)	0.092* (0.007)	0.019* (0.010)	−0.0006 (0.036)	0.0073 (0.0087)
Extent of clearing (IHS-transformed absolute amount in hectares)	0.010* (0.008)	0.009 (0.006)	0.043* (0.024)	0.047 (0.122)	0.012 (0.021)
Observations	63,882	51,432	11,712	738	63,882

Table shows the heterogeneous impact of titling on annual deforestation. Small, medium and large refer to different property sizes (see the Supplementary Information for the definitions). Overall refers to the average deforestation across property sizes. Weighted refers to the effect weighted by the size of the property. Numbers in parentheses are standard errors. We use heteroscedasticity-consistent (HAC) standard errors to account for spatial and dynamic correlation. *$P < 0.10$; **$P < 0.05$.

to a 0.2% increase in deforestation, but only on properties with a title. Hence, it seems that the existence of a title per se does not lead to deforestation, but the effect of changes in commodity prices (particularly, beef) mediates the effect of titling on deforestation in our sample.

As we compare farmers only with themselves using fixed-effects regression, we control for time-invariant characteristics such as slope, area, state and other variables that do not vary over time. Yet, we include the interaction effects of time-invariant characteristics such as agricultural suitability and distance to roads to account for the heterogeneous effects of temporal shocks on plots with different characteristics.

Our results contradict the conservation hypothesis, which posits that greater tenure security will lead to lower deforestation. Our data suggest that cattle prices (but not crop prices) have a stronger positive effect on deforestation for titled properties. One possible mechanism driving this effect is the greater integration with agricultural markets, possibly via the greater uptake of credit and investment in the land, which has been documented in evidence from case studies[22].

We disaggregate these effects (Table 1) to check for differences between property class sizes (small, medium and large; see the Supplementary Information for the definitions). Receiving a title increased the likelihood that clearing occurred on a property by 0.8% per annum (p.a.) relative to untitled properties (column 1 in Table 1). This effect is particularly pronounced for small and medium landholders. The likelihood that clearing occurs increases by 0.9% on small landholdings and by 1.9% on medium properties on average p.a. compared with those without titles. The extent of clearing also increases with land titling. This effect is most pronounced in medium properties, with an increase of 4.3% in the extent of deforestation compared with medium properties without titles. Large properties, in contrast, remained completely unaffected by the programme, with none of these coefficients showing consistent and significant signs. The fact that the weighted regression—which weighs the effect of each intervention by the size of the property—is not significant indicates that large farmers (who hold most of the forest area) do not respond to the intervention.

Our central robustness check of anticipatory behaviour (which we discussed for Fig. 1) is undertaken via an event study disaggregated for different property sizes (Fig. 2a–c). Our results show that farmers that possess smaller properties deforest substantially less (−1.8%) in the year before receiving the title, potentially due to interactions with forest authorities. It takes four years for the full effect of the title to materialize, potentially because it takes time to secure a loan and invest in the land. For farmers that hold medium plots, anticipatory behaviour has little effect, but deforestation increases substantially in the two years after receiving the title (5–9% and 7–9%). Famers with medium plots might already be better integrated into agricultural markets (as they probably produce substantially above the level of subsistence), and therefore the response to receiving the title is more immediate and sizeable than for the other two property types. In contrast, the deforestation pattern of large properties seems to be unaffected by the programme, both before and after receiving the title. This could be due to the central government's past efforts to curb deforestation on large properties, which are easier to monitor and sanction.

Discussion

We return to the main question of whether increased tenure security leads to greater conservation or to the contrary effect of higher rates of deforestation. The TLP may have contributed to a change in the behaviour of small and medium landholders, although in the opposite way to which it was intended. Large landholders, in contrast, remained largely unaffected by the programme. Yet, as our analysis indicates, the effect of property titles on deforestation is probably mediated by changes in agricultural commodity prices, particularly beef.

The effects of behaviour change with respect to deforestation, however, were different across time and property classes. Small landholders were the only property class that markedly altered their behaviour before they received the official title, potentially due to the contact with forest authorities. Famers with medium properties substantially increased deforestation one to two years after the title was received, whereas this ramp-up time took up to four years for farmers with small properties (probably because it takes more time for the latter farmers to secure credit for agricultural or cattle expansion). These results are in line with other studies on the effects of titling on agricultural investment. For example, Keswell and Carter[23] investigated the impacts of the land reform in South Africa, and found a time lag in recipients' increases in income of three to four years, due to the time it took to get a return on the investment in the title. A recent randomized control trial from Benin also suggested substantial increases in agricultural investment as a result of greater tenure security[24].

Our findings are also consistent with the limited number of studies in Latin America that have investigated the effect of land rights on deforestation. Liscow[25], using an instrumental variable approach, found that Nicaragua's agrarian reform has substantially increased deforestation. The underlying mechanisms he proposes of tenure security leading to increasing investment, agricultural productivity and increased returns to deforestation are also echoed in case study evidence. Wood and Walker[22] found that farmers with land titles were three times as likely to have access to credit than untitled farmers. In Brazil subsidized loans and microcredit policies are commonly used as mechanisms to achieve development goals. For instance, Assunção et al.[7] have shown that credit restrictions played a vital role in slowing deforestation in the Amazon, indicating that access to credit may analogously increase deforestation.

Our findings stand in contrast to those of L'Roe et al.[26], who studied the impacts of CAR enrolment in Brazil and its effect on properties

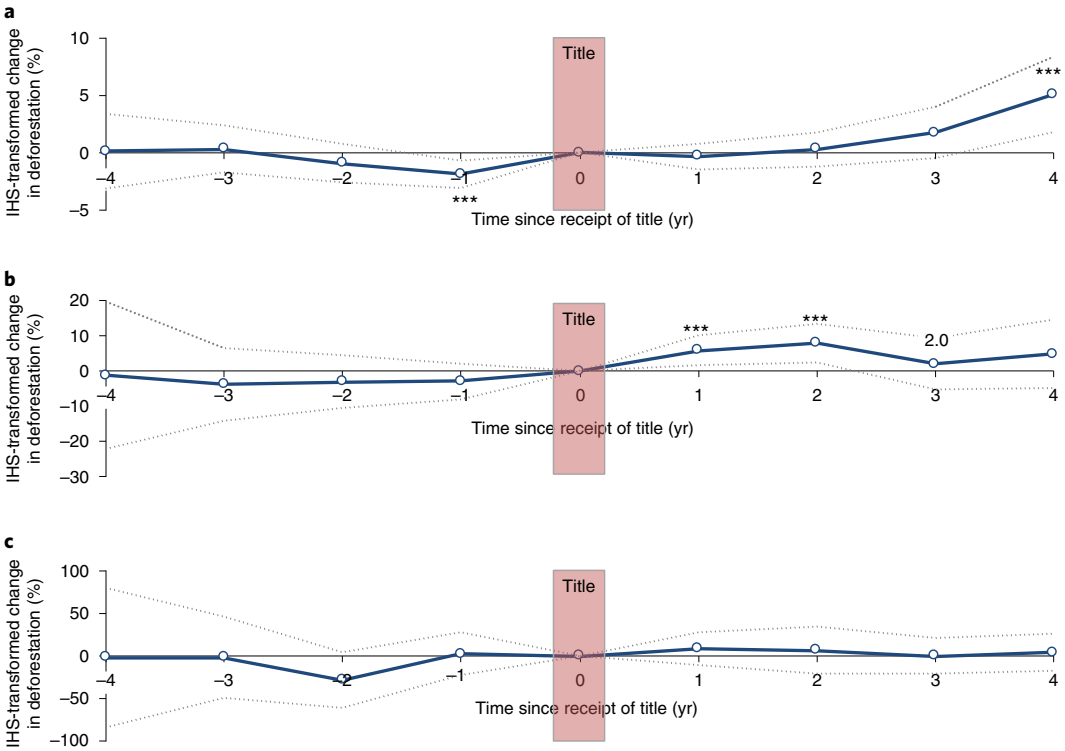

Fig. 2 | Time-specific effects of titling for plots of different sizes. a, Small plots. **b**, Medium plots. **c**, Large plots. ***$P < 0.01$.

Table 2 | Fixed effects model I with cattle and crop price interaction effects

Fixed effects main regression I						
Dependent variable: deforestation dummy						
	(1)	(2)	(3)	(4)	(5)	(6)
Title (0/1)	0.008** (0.004)	0.008** (0.004)	0.008 (0.004)	−0.018 (0.022)	0.005 (0.004)	−0.026 (0.022)
Corn prices $t-1$	-	0.0001 (0.0001)	0.00006 (0.0001)	−0.0001 (0.0002)	0.00009 (0.0001)	−0.0001 (0.0002)
Cattle prices $t-1$	-	-	0.0006 (0.0002)	0.0006 (0.0002)	0.0003 (0.0002)	0.0003 (0.0002)
Title × corn $t-1$	-	-	-	0.0002 (0.0002)	-	0.00009 (0.00003)
Title × cattle $t-1$	-	-	-	-	0.00009*** (0.00003)	0.00009*** (0.00003)
Time effects	Yes	Yes	Yes	Yes	Yes	Yes
Plot-level FE	Yes	Yes	Yes	Yes	Yes	Yes
Agr Suit × time	No	Yes	Yes	Yes	Yes	Yes
Distance to road × time	No	Yes	Yes	Yes	Yes	Yes
Observations	63,882	63,882	63,882	63,882	63,882	63,882
R^2-within	0.0027	0.0029	0.0030	0.0031	0.0032	0.0032

Title (0/1) is a dummy variable that switches from 0 to 1 once the property owner receives a formal title. Agr Suit refers to agricultural suitability. Cattle and corn prices are yearly average values. We use HAC standard errors to account for spatial and dynamic correlation. Distance to road is the IHS-transformed distance to roads in kilometres. FE, fixed effects. **$P < 0.05$; ***$P < 0.01$.

roughly the same size as those studied in our paper. They found that CAR registration, when paired with being registered in the TLP process, leads to sizeable reduction effects of deforestation. As CAR is a mechanism of environmental monitoring, and although it could be a first step towards tenure security, it seems to induce different behaviour than the TLP.

As with many studies comparing early and late enrollees in a programme, our results do not necessarily extend to farmers who never enrolled in the programme (and who may not have been interested in receiving a land title in the first place). We offer evidence on impacts among a large swath of the farming population who enrolled in the programme. Understanding drivers of

Table 3 | Fixed effects model II with cattle and crop price interaction effects

Fixed effects main regression II						
Dependent variable: percentage of property deforested						
	(1)	(2)	(3)	(4)	(5)	(6)
Title (0/1)	0.010 (0.008)	0.010 (0.008)	0.011 (0.008)	−0.007 (0.041)	0.005 (0.008)	−0.022 (0.042)
Corn prices $t-1$	-	0.0004 (0.0002)	0.0003 (0.0002)	0.0002 (0.0004)	0.0003 (0.0002)	0.0002 (0.0004)
Cattle prices $t-1$	-	-	0.0009** (0.0003)	0.0009** (0.0004)	0.0003 (0.0004)	0.0002 (0.0004)
Title × corn $t-1$	-	-	-	0.0002 (0.0004)	-	0.0002 (0.0004)
Title × cattle $t-1$	-	-	-	-	0.0002*** (0.00006)	0.0002*** (0.00006)
Time effects	Yes	Yes	Yes	Yes	Yes	Yes
Plot-level FE	Yes	Yes	Yes	Yes	Yes	Yes
Agr Suit × time	No	Yes	Yes	Yes	Yes	Yes
Distance to road × time	No	Yes	Yes	Yes	Yes	Yes
Observations	63,882	63,882	63,882	63,882	63,882	63,882
R^2-within	0.0003	0.0007	0.0007	0.0007	0.0007	0.0007

Title (0/1) is a dummy variable that switches from 0 to 1 once the property owner receives a formal title. Agr Suit refers to agricultural suitability. Cattle and corn prices are yearly average values. We use HAC standard errors to account for spatial and dynamic correlation. Distance to road is the IHS-transformed distance to roads in kilometres. **$P<0.05$; ***$P<0.01$.

deforestation among non-enrollees is an important topic for further research.

It is also clear that one of the channels that is commonly assumed to lower deforestation (namely, increased formal regulatory pressure) has not (yet) yielded a substantial effect on deforestation. This is not surprising given that many of the studied areas are remote. In addition, the TLP should be seen as the foundation for increased environmental monitoring in the future. Apart from budget constraints, TLP staff might also be worried that harsh sanctioning mechanisms (for example, expropriation) might yield lower cooperation from landholders.

Holders of larger properties did not alter their behaviour as a consequence of the titling programme. This is not unexpected given that large properties have faced increasing scrutiny since 2004 (ref. [12]). Larger landholdings are also easier to monitor through the DETER system, which uses remote sensing technology to detect deforestation in real time. It allows for quicker law-enforcement measures and has contributed to deforestation reductions in the past[5]. Recent empirical evidence from the Brazilian state Mato Grosso do Sul shows that larger farms showed a higher compliance with the Forest Code than smaller properties[27]. It could also be a result of more intensive agriculture instead of the historically dominant extensive agriculture due to better technology access and improved forest governance[28].

A central question that emerges from this research is how the requirements that the programme entails—particularly environmental conditions—can be more clearly communicated to landholders, while increasing the perceived regulatory pressure with the limited budget of $0.12 per hectare available to the programme[29]. Clearly, a closer collaboration with the environmental police and other departments would be warranted.

Given the responses of different landholders to the programme, a need arises to tailor the policy to these different class sizes. These differences also underline that close monitoring might need to start soon after the title is awarded to curb immediate clearing as was observed in the medium landholder group. Here it seems important in the initial steps, which include geo-referencing, to make participants aware of the requirements of the programme (for example, 80% of the property needs to remain forested as prescribed by the Forest Code). Given the low funding of the programme and the remoteness of many of those communities, this poses a substantial challenge to the administration. However, low-cost interventions (including various informational, design and content nudges), which have been successfully applied in other contexts, such as taxation, might serve as appropriate measures here as well[30].

Lastly, it should be noted that part of the clearing could be completely legal since the Forest Code allows for 20% clearing of forest cover in the Amazon on private properties. In addition, some amnesties were granted, which could have further intensified the perception among landholders that broader clearing is not sanctioned. These amnesties might have particularly increased incentives to deforest for landholders of small and medium properties, whereas large landholders were unaffected. Larger landholders are probably more aware of the requirements of the Forest Code given that in the past they have been the focus of stringent monitoring and enforcement through the DETER programme.

A number of limitations of our study should be underscored. First, the study period is limited to 2011–2016, and hence the effects of the TLP, particularly with the continuing rollout, can change in the future. Second, while we show (Methods) that titling across different years displays relatively constant characteristics, in the absence of randomization or a viable instrumental variable, we cannot fully eliminate the possibility of omitted variable bias. Nonetheless, as noted in the 'Pre-trend analysis' section, we have strong reasons not to believe that this is the case. Third, in the absence of credit uptake data, which unfortunately are not collected by the programme, our hypothesis that increased deforestation is explained mainly through the greater uptake of credit cannot be fully explored and is based on evidence from other studies[7,22]. Nonetheless, we show that deforestation on titled properties reacts more strongly to changes in market prices, indicating a greater integration into agricultural (and potentially credit) markets. Fourth, other factors apart from forest conservation, such as poverty alleviation and conflict reduction, are goals that the Brazilian government is pursuing with the TLP programme. Declarations by former President Michel Temer that parts of protected areas might be opened up for agriculture yielded

the worst land-related killings in 21 years and give a sense of the ferocity of environmental conflicts in the absence of clearly defined land rights[31]. Fifth, our study does not evaluate deforestation outside of rural properties or whether landholders comply with legislation by restoring or offsetting native vegetation elsewhere if not in compliance with the minimum required by the Forest Code. Sixth, it is important to note that the TLP converts a relatively small share of undesignated areas to private land, with the rest being assigned to conservation units and indigenous reserves. Hence, our analysis extends only to the effect of the TLP on these farmers, not the entire policy.

In sum, our results underline that titling initiatives per se should not be seen as a mechanism to reduce deforestation. If titling increases the access to credit and agricultural markets, then increased tenure security can have the opposite effect of the original policy goal. Our results suggest that cattle prices in particular play an important role in informing land-use decisions. Hence, integrating the TLP more strongly with other policies is warranted to counter the negative environmental consequences that increased tenure security may entail. Given that many landholders are credit constrained, a greater integration between credit programmes is a worthwhile starting point. Studying the impact of integration between land titling and other environmental policies also warrants further investigation. In addition, livelihood impacts of the TLP programme remain unclear and could be the focus of future work.

Methods

Data. Data on the geo-referenced properties were provided directly by the Secretariat for Land Title Regularisation in the Legal Amazon (SERFAL), which is responsible for the programme. Deforestation data (PRODES) were downloaded from the Instituto Nacional de Pesquisas Espaciais[32]. Given the frequent case of 0 for deforestation, we transformed the deforestation variable by adding half of the minimum value of deforestation in the dataset to each observation of deforestation. It is likely that some deforestation takes place on most plots, but these amounts are below the minimum value that the deforestation detection programme PRODES can pick up. In our case, we transformed annual deforestation in hectares with an IHS transformation, which has emerged as a suitable alternative to taking the log in cases with zeros in the data[33]. Climate data were downloaded from WorldClim, and the monthly data were converted to yearly mean values[34]. Similarly, the distance to roads was analysed with Open Street Map, representing highways circa 2010. Agricultural suitability and slope data were downloaded from the Centro de Sensoriamento Remoto[35].

We collected agricultural prices from the Agriculture and Supply Secretariat of the State of Paraná (SEAB-PR). Although Paraná is not part of the Legal Amazon, its prices are strongly correlated with local crop prices in the municipalities in the Brazilian Amazon.[36] The set of agricultural commodities are rice, mandioca, cassava, corn and sugarcane, which account for circa 70% of the total harvested area in the sample municipalities. We constructed an annual municipality-specific price index for these crops. We began by averaging the prices for each year and crop and deflated prices to 2011 Brazilian reais to compute an index with 2011 as the base year. We then calculated a weighted real price for each municipality and year:

$$PA_{itc} = \sum \frac{A_{ic}}{TA_{i\,2011}} \times P_{tc\,2011} \quad (1)$$

where PA_{itc} is the weighted real price of crop c in municipality i at time t. A_{ic} is the area of land in i dedicated to c, TA_{i2011} is the total area that was dedicated to the five investigated crops in i in 2011, and P_{tc2011} is the real price of c in Paraná at t expressed an index with base year 2011. The first term on the right side represents the relative importance of c in the agricultural production of i at the beginning of our sample period.

We also constructed an index of cattle prices, which have been shown to act as a strong pull factor on deforestation. Using the SEAB-PR data, we derived an annual cattle price index in a similar fashion to equation (1). However, since there is no information on the area dedicated to cattle, we use the number of cattle per i in 2011 as a municipality-specific weight. We derive both indices for the 149 distinct municipalities in our sample.

It is important to underscore one peculiarity of the PRODES data, which is that annual deforestation maps for year t run from August $t-1$ to July t (for example, deforestation for 2014 runs from August 2013 to July 2014). Hence, we recoded all variables (such as whether the land was titled in a given year) to correspond to the PRODES timeframe. We therefore also employ beef and crop prices in the year $t-1$, which accounts for the timing of agricultural production in the Legal Amazon. Given that the regional dry season extends from June through September, crops are sown between October and December, and harvested the next year until May. For farmers to derive the optimal value from their harvest, previous studies have shown that farmers probably observe prices in early $t-1$ for land-use decisions, which should then be evident in deforestation rates between August $t-1$ and July t (ref. [36]).

The spatial data were processed in QGIS[37] (version: 2.18 'Las Palmas') and subsequently analysed in R Studio[38] (version: 1.1.383) and Stata[39] (version: 13.1). PRODES deforestation maps, temperature data and precipitation data were split into yearly shapefiles or tiff files and intersected with the geo-referenced property maps provided by SERFAL to extract the yearly amount of deforestation and climate variation on each property. For calculations involving distance measures (for example, distance to roads of properties), equidistant projections were used, whereas for deforestation measures, projections yielding equal area were employed.

The first two years of the programme, which account for only a minor fraction of the titles, were excluded due to irregularities and database issues. Until May 2011, 611 titles were granted, almost one-third in Novo Progresso in Pará. Some of these titles were also migrated from another system and therefore may represent claims that resulted before the programme period. In addition, these plots were almost six times as large as plots titled in Pará between 2011 and 2016, indicating irregularities in the titling procedure. Indeed, a joint operation by the federal police (IBAMA), the Federal Reserve and the Public Federal Ministry in Novo Progresso captured a criminal organization specializing in environmental crimes and land-grabbing, with damages estimated to have reached 500 million reais. Part of the scheme was to register illegally seized properties in the TLP with falsified documents and subsequently sell the land[40].

Supplementary Tables 2 and 3 show the number of titled plots across eight Amazonian states in the period 2012–2016 (data from Roraima were excluded due to data availability issues). Of these plots, 44% were titled in 2012–2014, whereas 56% were titled in 2015–2016 (as previously mentioned, the titling dates were recoded to correspond to the PRODES deforestation data, which use the seasonal year). As discussed, since properties that were officially listed as being titled in 2009 or 2010 could have been transferred from a different policy with an earlier titling date, these years were excluded from the main analysis. By far the largest registration took place in 2015, when 42% of the properties were titled.
The relative number of titles per class size also remains largely similar across different years. In addition, while more than 80% of titles were registered by small property owners, they account for only around 40% of the overall area, comparable to the area of medium property owners, even though they represent less than 20% of registered plots.

Across states, the mean area of titled plots remained relatively constant at close to 50 hectares (Supplementary Fig. 7). Whereas in 2014 the registered plots tended to be larger, the plot size across the studied period remained relatively constant. In addition, the mean deforestation on these plots before the programme in 2000–2009 was relatively similar across titled years, with a slightly decreasing trend over time. As we estimate the impact of the TLP by comparing earlier titled plots with those titled later, and later titled plots seem to have lower opportunity costs (for example, due to the suitability of the land for agricultural purposes), there is a chance that the impacts of titling are slightly underestimated. Therefore, if prior deforestation is used a proxy for the opportunity costs that plots face, our estimates may represent the lower bound of the impact given that later plots may face slightly lower opportunity costs.

This is supported by the agricultural suitability data, which show a slightly decreasing trend. It is noteworthy, however, that the agricultural suitability data show that the titled plots are on average suitable for agriculture (with a mean around 1, which indicates suitable but is far from the maximum value of 2 (very suitable)).

In addition, it is striking that the distance to roads of titled plots remains relatively constant in the period analysed, indicating that no systematic difference in accessibility between earlier and later plots exists. The properties titled in 2016 were excluded, since for our empirical strategy each property should have at least one year of deforestation data after receiving the title.

These data indicate that plots titled early (2012–2013) present a credible counterfactual to those titled later (2014–2015). This is tested more formally in the next section.

Pre-trend analysis. This section describes the methods employed in our pre-trend analysis. This analysis tests more rigorously the integral assumption underpinning the estimation strategy—namely, that properties registered later in the process can be used as a credible counterfactual to those registered earlier[41]. The majority of properties in the programme are relatively small, and hence their occupants probably have limited political power to increase the speed and location of titling campaigns, which are organized centrally in Brasilia. In addition, farmers have to prove that they have occupied the plot of land since at least 2008, and a central federal committee in Brasilia (which remains largely uninfluenced by local politics) checks these claims.

While the above assumption remains difficult to fully prove, two different approaches were employed to formally test this assumption to complement the foregoing analysis. First, to check whether the treatment assignment (that is,

titling) was correlated with the contemporaneous rate of deforestation in the municipality, the yearly change in the proportion of the municipality that was deforested was regressed on the number of titles issued. None of the coefficients is significant, regardless of whether municipality or year fixed effects are introduced, which can be seen in Supplementary Table 6.

Second, in line with Alix-Garcia et al.[2], deforestation data from before the programme were used to test whether the assumption would hold in the period before the programme. We ran a fixed-effects regression on the deforestation data from 2007–2010, using time effects to account for temporal shocks. As can be seen in Supplementary Table 7, this regression was calculated using an interaction term between a time trend and a dummy variable that indicated earlier registered cohorts. The analysis was also segregated to account for year-to-year variations.

The time trend is not significant across years, suggesting that trends across cohorts did not differ significantly. Even if the trends are further disaggregated into different years, the coefficients for the single years are not significant. This supports our assumptions underpinning the estimation strategy.

Main empirical analysis. Impact evaluation in quasi-experimental settings, as discussed earlier, commonly struggles with non-random treatment assignment. This means that treatment assignment could be spatially and/or temporally correlated with the dependent variable (deforestation rates in our study). For instance, treatment assignment could, in principle, be correlated with distance to roads, which fosters the integration with markets. This, in turn, may make the conversion to agricultural land or timber harvesting more profitable. Unless these confounding factors, both observed and unobserved, are controlled for, this could unduly alter the results. We show in our pre-trend analysis no systematic differences in the factors across years for the titled properties.

A number of specification tests were performed to clarify whether fixed effects, random effects or pooled ordinary least squares (OLS) were required. First, using a Breusch–Pagan Lagrange multiplier, we reject the hypothesis that a pooled OLS will produce unbiased results. This makes an individual-effects model (random or fixed effects) necessary. Using a Hausman and Chow test, we find that year-fixed effects and property-level fixed effects are warranted[42].

We therefore estimate a fixed-effects model, combined with a vector of control variables that are both time and space variant. We estimate:

$$Y_{it} = \gamma_i + \delta_t + \beta_1 \mathbf{D}_{it} + \beta_2 X_{it} + \varepsilon_{it} \quad (2)$$

where i indexes the properties and t the years, Y is a binary indicator of whether any deforestation occurred (and in a second step, a IHS-transformed measure for the change in the amount in a specific year), γ are the property-level fixed effects, δ are the time-fixed effects, $\mathbf{D}$ is a vector of dummy variables for titling, X are control variables that vary over time, β_1 and β_2 are parameters to be estimated, and ε is the error term. The property-level fixed effects account for time-invariant location-specific characteristics, whereas the time-fixed effects control property-invariant time effects. We estimate the equation using OLS and cluster standard errors using HAC standard errors, which correct for cross-sectional spatial dependence and panel-specific serial correlation. This approach therefore accounts for the dynamic nature of land-use change. We account for serial correlation for the entire duration of the programme (six years) and cluster standard errors using a distance cut-off of 10 km around the property. We consider the cut-off in relation to the spatial extent of each treatment unit. Hence, for a ~5-hectare farm, with dimensions ~0.25 km × 0.25 km, a 10 km buffer means that we are considering effects as far away as 40 times the farm size (or 40 contiguous farm plots away). Despite the dependent variable being a binary variable in the first model, we use a linear model for ease of interpretation, which for moderate levels of probability gives similar estimates while being easier to interpret than logistic probability models. In a second step, the yearly amount of deforestation in hectares on the plots was IHS-transformed to indicate the change in absolute deforestation. Given the common values of zero for deforestation, we transformed the deforestation variable via an IHS transformation.

To consider the effect of receiving the formal property title, a dummy variable is introduced that switches from 0 to 1 once the title is received. To test whether the effect of titling changes across time (for example, it might not be as strong after one year, since the perceived regulatory pressure wanes) and whether anticipatory effects are present, we introduce in the event study used as a robustness check dummy variables to capture the time the title was received. This approach is in line with similar studies[41] and accounts for possible short-term effects of titling.

To distinguish the effects that titling has across property sizes and time, we split the sample across módulos fiscais (MFs). The latter is a unit of measure in hectares and, depending on the state, can be between 5 and 110 hectares for each MF. In the Legal Amazon, one MF has on average 76 hectares, but size is heterogeneous across municipalities. In line with the Brazilian law, we split the sample into small properties (<1 MF), medium properties (1–4 MFs) and large properties (4–15 MFs). Commonly, 1–4 MFs are referred to as semi-small and 4–15 as medium, but we chose these categories for ease of interpretation and given the scope of the TLP.

In our main analysis, we include the size of the property as a continuous variable but later split the sample by property sizes. Analysing the difference between property size classes is also important since landowners pay different prices to receive the land titles depending on the size. Owners of small properties, below 1 MF, receive the property title for free. Owners of medium properties, between 1 and 4 MFs, pay a modest fee that covers the cost of the titling process (for example, geo-referencing and administrative costs). Owners of large properties need to pay a higher titling fee, which commonly amounts to 20–30% of the market price of the enrolled land (this has been revised in the most recent version of the law, which was enacted after the time period we consider in this study). These differences stem from a supposed difference in income between the different classes of landowners. Another important factor is that large properties are the only ones to be visited by the TLP to verify their claims on-site. This may incentivize some landholders to register into the programme only a proportion of their property, which is below 4 MF.

Lastly, control variables for state heterogeneity (dummies for each state, where the policy is implemented) were introduced, as well as climate controls (precipitation and temperature), agricultural suitability, slope, and crop and beef prices.

Our empirical strategy tests the assumption that titled properties display a different clearing pattern than those that are not titled yet. The original premise of the TLP is that with increased formal regulatory pressure and tenure rights, deforestation is likely to decrease. However, in principle, greater integration with public and private credit programmes could also have the opposite effect if investments into extensive agriculture increase the return to deforestation, as demonstrated by Liscow[25] in the case of Nicaragua.

As discussed previously, a possible bias of our estimation results is that unobserved time-variant heterogeneity between properties might be driving the observed results. However, as indicated, we believe that this is unlikely, since titling is influenced by credible exogenous factors.

Data availability

The data that support the findings of this study are available from SERFAL, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. The data are, however, available from the authors upon request and with the permission of SERFAL. Source data are provided with this paper.

Code availability

The code is available from the corresponding author upon request.

Received: 25 April 2019; Accepted: 7 April 2020;
Published online: 18 May 2020

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Author contributions

B.P., A.B. and A.K. contributed equally to the paper. T.N.P.d.R. was responsible for the collecting the deforestation data and revising the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41893-020-0537-2.

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